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Presenters

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Dr. Joshua Perkel is a Research Engineer in the Assessment group at NEETRAC. He has worked in the Power Cable arena for more than 5 years. Josh holds a PhD in electrical engineering from the Georgia Institute of Technology.

CDFI Contributors

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Joshua Perkel

CDFI Meeting - Aug. 19-20 San Ramon, CA
Day 1

<table>
<thead>
<tr>
<th>Time</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>12:00 – 13:00</td>
<td>Lunch</td>
</tr>
<tr>
<td>13:00 – 13:10</td>
<td>Welcome</td>
</tr>
<tr>
<td>13:10 – 13:30</td>
<td>NEETRAC Overview</td>
</tr>
<tr>
<td>13:30 – 14:00</td>
<td>CDFI Background/Overview</td>
</tr>
<tr>
<td>14:00 – 14:30</td>
<td>Cable System Failure Process</td>
</tr>
<tr>
<td>14:30 – 14:45</td>
<td>SAGE Concept</td>
</tr>
<tr>
<td>14:45 – 15:00</td>
<td>Break</td>
</tr>
<tr>
<td>15:00 – 16:00</td>
<td>Case Study: Roswell</td>
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<tr>
<td>16:00 – 16:30</td>
<td>Diagnostic Accuracies</td>
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<tr>
<td>16:30 – 17:00</td>
<td>Diagnostic Testing Technologies (Part I)</td>
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Day 2

<table>
<thead>
<tr>
<th>Time</th>
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<tr>
<td>07:30 – 08:00</td>
<td>Continental Breakfast</td>
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<tr>
<td>08:00 – 08:15</td>
<td>Review Day 1</td>
</tr>
<tr>
<td>08:15 – 09:30</td>
<td>Diagnostic Testing Technologies (Part II)</td>
</tr>
<tr>
<td>09:30 – 10:00</td>
<td>Accuracies Really Matter</td>
</tr>
<tr>
<td>10:00 – 10:15</td>
<td>Break</td>
</tr>
<tr>
<td>10:15 – 11:20</td>
<td>The Things We Know Now That We Did Not Know Before</td>
</tr>
<tr>
<td>11:25 – 11:45</td>
<td>Selecting a Diagnostic Testing Technology</td>
</tr>
<tr>
<td>11:45 – 12:00</td>
<td>Summary</td>
</tr>
<tr>
<td>12:00 – 13:00</td>
<td>Lunch</td>
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</tbody>
</table>

Outline

- NEETRAC Overview
- CDFI Background/Overview
- Cable System Failure Process
- SAGE Concept
- Case Study: Roswell
- Diagnostic Accuracies
- Diagnostic Testing Technologies
- Accuracies Really Matter
- The Things We Know Now That We Did Not Know Before
- Selecting a Diagnostic Testing Technology
- Summary
Background

- Created in 1996 when Georgia Power donated the facilities of its Research Center to Georgia Tech.
- Set up as a self-supporting center within the School of Electrical and Computer Engineering of the Georgia Tech.
- NEETRAC is a membership-based center, conducting research programs for the Electric Energy Transmission and Distribution Industry.

NEETRAC Mission & Vision

Mission
To provide a venue where NEETRAC Staff, NEETRAC Members and the Georgia Tech Academic community can collaborate to solve problems in the T&D Arena.

Vision
We will build on our expertise to become the leading national Center for collaborative applied and strategic research and development for electric transmission and distribution.

Members 2009-2010

1. 3M
2. ABB
3. Ameren Services
4. American Electric Power
5. Baltimore Gas & Electric
6. British Columbia Hydro
7. Borealis Compounds LLC
8. Con Edison
9. Cooper Power Systems
10. Dominion/Virginia Power
11. Dow Chemical Company
12. Duke Energy
13. Entergy
14. Exelon
15. First Energy
16. Florida Power & Light
17. GRESCO Utility Supply
18. Hubbell
19. NRECA
20. NSTAR
21. PacifiCorp
22. Prysmian Cables & Systems
23. Public Service Electric & Gas
24. S&C Electric Company
25. South Carolina Electric & Gas
26. Southern California Edison
27. Southern Company
28. Southern States
29. Southwire
30. Thomas and Betts/Homac
31. TVA
32. tyco/Raychem
33. Zenergy Power
NEETRAC Membership Growth

<table>
<thead>
<tr>
<th>Year</th>
<th>Members</th>
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<tbody>
<tr>
<td>1996</td>
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<tr>
<td>2008</td>
<td></td>
</tr>
<tr>
<td>2010</td>
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</table>

Members

- Utility Members
  - Provide > 50% of power sold in the US
  - Serve over 64,000,000 customers
- Manufacturing Members
  - Primary suppliers of T&D equipment to electric utilities in the United States

Focus Areas Developed

<table>
<thead>
<tr>
<th>PRIMARY FOCUS AREA</th>
<th>FOCUS SEGMENTS</th>
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</thead>
<tbody>
<tr>
<td>Hardware/Equipment Testing</td>
<td>Application Research, Product Evaluation, Engineering Analysis &amp; Support, Equipment Spec. &amp; Test Protocol Development</td>
</tr>
<tr>
<td>New Technology/Research</td>
<td>Research, System Enhancements</td>
</tr>
<tr>
<td>Reliability</td>
<td>Asset Management, Condition Assessment, Forensics</td>
</tr>
<tr>
<td>System Analysis</td>
<td>Operation, Installation, Design, Power Quality/Grounding, Safety, Training/Education</td>
</tr>
</tbody>
</table>

Facilities: High Voltage Lab
Facilities: Low Voltage & Mechanical Lab

Staff

- 25 Research Staff
  - Ph.D degrees (EE & Physics)
  - M.S. degrees (EE, IE, & ME)
  - Bachelors degrees (EE & ME)
- 5 Administrative and IT Support
- 1 Coop Students
This is NEETRAC

- 25 Research Staff
- 5 Administrative Support Staff
- Academic Faculty
- Co-op and Graduate Students

Outline

- NEETRAC Overview
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CDFI Background

- Underground cable system infrastructure is aging (and failing). Much of the system is older than its design life.
- Not enough money / manufacturing capacity to simply replace cable systems because they are old.
- Need diagnostic tools that can help us decide which cables/accessories to replace & which can be left in service.
- Always remember that we are talking about the cable SYSTEM, not just cable.

Why do we need diagnostics?
Overview

• In the CDFI, NEETRAC worked with 17 utilities, 5 manufacturers and 5 diagnostic providers to achieve the objective of clarifying the concerns and defining the benefits of diagnostic testing.

• Phase 1 has almost exclusively focused on aged medium voltage systems.

• This is the largest coherent study of cable system diagnostics anywhere.
CDFI Background/Overview

CDFI Meeting - Aug. 19-20 San Ramon, CA

Participants

<table>
<thead>
<tr>
<th>Participants</th>
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<tbody>
<tr>
<td>American Electric Power</td>
</tr>
<tr>
<td>Ameren</td>
</tr>
<tr>
<td>Cablewise / Utilx</td>
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<tr>
<td>CenterPoint Energy</td>
</tr>
<tr>
<td>Con Edison</td>
</tr>
<tr>
<td>Cooper Power Systems</td>
</tr>
<tr>
<td>Duke Power Company</td>
</tr>
<tr>
<td>Exelon (Commonwealth Edison &amp; PECO)</td>
</tr>
<tr>
<td>First Energy</td>
</tr>
<tr>
<td>Florida Power &amp; Light</td>
</tr>
<tr>
<td>Georgia Tech</td>
</tr>
<tr>
<td>GRESCO</td>
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<tr>
<td>HDW Electronics</td>
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<td>Hydro Quebec</td>
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<td>IMCORP</td>
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<tr>
<td>NRECA</td>
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<td>PacifiCorp (added mid 2005)</td>
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<tr>
<td>Pacific Gas &amp; Electric (added Jan 06)</td>
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<tr>
<td>PEPCO</td>
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<tr>
<td>Oncor (TXU)</td>
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<tr>
<td>Prysmian</td>
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<tr>
<td>Public Service Electric &amp; Gas</td>
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<tr>
<td>Tyco / Raychem</td>
</tr>
<tr>
<td>Southern California Edison</td>
</tr>
<tr>
<td>Southern Company</td>
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<tr>
<td>Southwire</td>
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<td>Hydro Quebec</td>
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<td>Southern California Edison</td>
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<tr>
<td>Southern Company</td>
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<tr>
<td>Southwire</td>
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</tbody>
</table>

CDFI - Primary Activities

1) Technology Review
2) Analysis of Existing (Historical) Data
3) Collection and Analysis of Field (New) Data
4) Verification of VLF Test Levels
5) Defect Characterization
6) Develop Knowledge Based System
7) Quantify Economic Benefits
8) Reports, Update Meetings and Tech Transfer Seminars

Analyses are data / results driven

CDFI Background/Overview

CDFI Meeting - Aug. 19-20 San Ramon, CA

CDFI Activities

- Analysis
- Lab Studies
- Field Studies
- Dissemination

CDFI Background/Overview

CDFI Meeting - Aug. 19-20 San Ramon, CA

CDFI Activities

- Analysis
  - Value / Benefit
  - Accuracies
  - Utility Data
  - IEEE Std Work
  - Knowledge Based Systems
- Lab Studies
  - VLF Withstand
  - Tan δ
  - PD
- Field Studies
  - Georgia Power
  - Duke
- Dissemination
  - Handbook
  - Publications
  - Meetings
  - Industry
  - CDFI

CDFI Background/Overview

CDFI Meeting - Aug. 19-20 San Ramon, CA
CDFI Activities

Lab Studies

VLF Withstand
- Test Time
- Test Voltage
- Forensics

Tan δ
- Time Stability
- Voltage Stability
- Non-Uniform Degradation
- Neutral Corrosion

PD
- Calibration
- Phase Pattern
- Feature Extraction
- Classification

CDFI Activities

Field Studies

Georgia Power
- XLPE
- Jkt & UnJkt
- 21 Conductor Miles
- Offline PD (0.1Hz)
- Offline PD (60Hz)
- Tan δ
- Monitored Withstand

Duke
- XLPE & Paper
- Jkt & UnJkt
- 20 Conductor Miles
- Offline PD (0.1Hz)
- Tan δ
- Monitored Withstand

Utilities

Analysis
- 89,000 Conductor Miles

Value / Benefit

Accuracies

Utility Data

IEEE Std Work

Knowledge Based Systems

Economic Model

SAGE

DC Withstand
- Offline PD
- Online PD
- Tan δ
- VLF Withstand

400 Omnibus
- 400.2 VLF

Survey Expert System Application

CDFI Activities

Utility Data

Con Ed

Com Ed

PPL

Alabama Power

Keyspan

DC Withstand
- Offline PD (60Hz)
- Online PD
- Tan Delta
- VLF Withstand

Offline PD (0.1Hz)
- Online PD
- Offline PD (0.1Hz)
- Tan Delta
- VLF Withstand

CDFI Background/Overview
CDFI Activities

Utility Data

- FPL
- PEPCO
- PG&E
- ONCOR
- Ameren

Offline PD (60Hz)
VLF Withstand
Offline PD (0.1Hz)
Online PD
VLF Withstand
Online PD (60Hz)
Online PD
Tan δ

CDFI Background/Overview

Dataset Sizes

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Technique</th>
<th>Laboratory [Conductor miles]</th>
<th>Field [Conductor miles]</th>
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</thead>
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<td>Diagnostic</td>
<td>DC Withstand</td>
<td>-</td>
<td>78,105</td>
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<td>Monitored Withstand</td>
<td>-</td>
<td>149</td>
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<tr>
<td></td>
<td>PD Offline</td>
<td>2</td>
<td>490</td>
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<tr>
<td></td>
<td>PD Online</td>
<td>-</td>
<td>262</td>
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<tr>
<td></td>
<td>Tan δ</td>
<td>1.5</td>
<td>550</td>
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<tr>
<td></td>
<td>VLF Withstand</td>
<td>1.5</td>
<td>9,810</td>
</tr>
<tr>
<td></td>
<td>IRC</td>
<td>0.3</td>
<td>-</td>
</tr>
<tr>
<td>Service Performance</td>
<td>ALL</td>
<td>89,000</td>
<td></td>
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</tbody>
</table>

CDFI Background/Overview

Benefits from Diagnostic Programs

Decreasing failures associated with diagnostics and actions

At the Start

- For many utilities, the usefulness of diagnostic testing was unclear.
- The focus was on the technique, not the approach.
- The economic benefits were not well defined.
- There was almost no independently collated and analyzed data.
- There were no independent tools for evaluating diagnostic effectiveness.
Where we are today (1)

1. Diagnostics work – they tell you many useful things, but not everything.
2. Diagnostics do not work in all situations.
3. Diagnostics have great difficulty definitively determining the longevity of individual devices.
4. Utilities HAVE to act on ALL replacement & repair recommendations to get improved reliability.
5. The performance of a diagnostic program depends on
   • Where you use the diagnostic
   • When you use the diagnostic
   • What diagnostic you use
   • What you do afterwards

Where we are today (2)

6. Quantitative analysis is complex BUT is needed to clearly see benefits.
7. Diagnostic data require skilled interpretation to establish how to act.
8. No one diagnostic is likely to provide the detailed data required for accurate diagnoses.
9. Large quantities of field data are needed to establish the accuracy/limitations of different diagnostic technologies.
10. Important to have correct expectations – diagnostics are useful but not perfect!

Overview

• In the CDFI, NEETRAC worked with 17 utilities, 5 manufacturers and 5 diagnostic providers to achieve the objective of clarifying the concerns and defining the benefits of diagnostic testing.

• We have come a long way wrt the project objective.
  – Analysis driven by data / results
  – Developed a good understanding that diagnostic testing can be useful, but the technologies are not perfect.
  – Developed ways to define diagnostic technology accuracy and found ways to handle inaccuracies.
  – Developed diagnostic technology selection and economic analysis tools.
  – Understand that there is yet more to learn.

QUESTIONS
Outline

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How things fail and what fails have a big impact on the selection of diagnostics

Cable System Failure Process

Failures by Equipment

Failure Rates

<table>
<thead>
<tr>
<th>Failure Rate [#/100 Miles/Year]</th>
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<tbody>
<tr>
<td>Lower Quartile: 1.6</td>
</tr>
<tr>
<td>Median: 3.5</td>
</tr>
<tr>
<td>Upper Quartile: 8</td>
</tr>
<tr>
<td>Mean: 12</td>
</tr>
<tr>
<td>Maximum: 140</td>
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</table>

Peak at 140
Failure Rate Estimates – By Equipment

<table>
<thead>
<tr>
<th>Rate Type</th>
<th>Rate</th>
</tr>
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<tbody>
<tr>
<td>Cable Rate</td>
<td>8.0</td>
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<tr>
<td>Splice Rate</td>
<td>7.0</td>
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<tr>
<td>Term Rate</td>
<td>6.0</td>
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<tr>
<td>Link Rate</td>
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<tr>
<td></td>
<td>4.0</td>
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<td>3.0</td>
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</table>

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Major Cable Components

Extruded
- Conductor
- Conductor Shield
- Insulation
- Insulation Shield
- Metallic Shield/Neutral
- Jacket (Recommended)

PILC
- Copper Conductor
- Interinsulation Phase Insulation
- Insulation Shield
- Paper and Copper Tape Core Binder
- Lead Sheath
- PVC or PE (Green Jacket)

http://www.otds.co.uk/cables.php

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Defect Types in Extruded Cables
1. Cavity at shield(s)
2. Cavities due to shrinkage
3. Insulation shield defect
4. Contaminant (poor adhesion)
5. Protrusions at shield(s)
6,7 Splinter/Fiber
8. Contaminants in insulation or shields

CDFI Meeting - Aug. 19-20 San Ramon, CA

Conversion of Water to Electrical Trees
- Acts as a stress enhancement or protrusion (non-conducting)
- Water tree increases local electric field
- Water tree also creates local mechanical stresses
- If electrical and mechanical stresses high enough ⇒ electrical tree initiates
- Electrical tree completes the failure path – rapid growth

Electrical tree growing from water tree

CDFI Meeting - Aug. 19-20 San Ramon, CA
Summary

• Cable system aging is a complex phenomenon.
• Multiple factors cause systems to age.
• Increases in dielectric loss and partial discharge are key phenomenon.
• The aging process is nonlinear.
• Diagnostics must take these factors into consideration.
Outline

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SAGE Approach to Diagnostic Programs

Diagnostic Program Phases - SAGE

Selection
Data compilation and analysis needed to identify circuits that are at-risk for failure (at-risk population).

Action
Determine what actions can be taken on circuits based on the results of diagnostic testing.

Generation
Conduct diagnostic testing of the at-risk population.

Evaluation
Monitor at-risk population after testing to observe/improve performance of diagnostic program.

SAGE at Work

Selection
Action
Generation
Evaluation

Decreasing Failures
Increasing Failures

SAGE Concept
### Context – is important

- **Data**
  - Generation from Diagnostic Measurement

- **Local Context**
  - Comparisons within one area

- **Global Context**
  - Comparison with many tests
  - Databases
  - Standards

---

### When to deploy diagnostics

- **Increasing Failures**
- **Decreasing Failures**
- **Continued Failure Increase**

---

### QUESTIONS
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- **Case Study: Roswell**
- Diagnostic Accuracies
- Diagnostic Testing Technologies
- Accuracies Really Matter
- The Things We Know Now That We Did Not Know Before
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Case Study
Roswell, GA
November 2008 & January 2009

- TDR
- Tan Delta
- Monitored Withstand
- Offline PD

Roswell Map

Selección
Roswell Background Info.

- 1980 vintage XLPE feeder cable, 1000 kcmil, 260 mils wall, jacketed.
- Failures have occurred over the years – no data on source
- Recently experienced very high failure rates of splices on this section: 80 failures / 100 miles / yr.
- Overall there have been 10 -15 failures of these splices in last two years on a variety of GPC feeders.
- Splice replacement may be acceptable if there is a technical basis.

Knowledge Based Selection System

<table>
<thead>
<tr>
<th>Diagnostic Technique</th>
<th>Action Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Replace Small Portion</td>
<td>VL-69 Mins, VLF 15 Mins</td>
</tr>
<tr>
<td>Replace Segment</td>
<td>VLF 30 Mins, DC Witsland</td>
</tr>
<tr>
<td>Replace Accessories</td>
<td>VLF 60 Mins, HV DC Leakage</td>
</tr>
</tbody>
</table>

Summary for Diagnostic Selection

Have a shortlist of three techniques:

- Replace Small Portion
- Replace Segment
- Replace Accessories
Economic Details – prior to testing

- Complete System Replacement $1,000,000 approx
- Complete Splice Replacement $60,000
- Test time (determined by switching) 3 - 4 Days
- Selection Costs $5,000
- Splice Replacement 7 Days
- Retest after remediation 1 Day

Monitored Withstand, Offline PD and VLF (30 mins) offer economic benefit over doing nothing.

Scenario Assessment before Testing

Offline PD
- If 51,000ft is tested
- 0.5% fails on test, no customer interrupted
- 1 site / 1,000ft (median)
- 40% discharges in cable
- Estimate
  - 0 fails on test
  - 51 discharge sites
    - 20 cable,
    - 31 accessories
  - 15 splices
  - <2 failure in 12 months from test

Monitored Withstand
- If 51,000ft is tested
- <4% fails on test, no customer interrupted
- 70% of loss tests indicate no further action
- Estimate
  - <2 fails on test
  - 3 assessed for further consideration by loss
  - 0.5 failure in 12 months from test

Initial Corrective Action Options

- Replace splices only – no detailed records assume 12 splices.
- Complete system replacement.
GENERATION

Overhead and Cabinet Terminations

Tan $\delta$ Monitored Withstand

If this had been a Simple Withstand

No Failures On Test

18 Segments Tested
**Monitored Withstand - Stability**

- 18 Segments Tested
- Pass - Stable Loss
- Pass - Un Stable Loss

**Sequence of Lengths Tested (miles)**

- 60 min test
- 30 min test

**Test Results - Local Perspective**

- Tip Up 1.5Uo - 0.5 Uo (1e-3)
- Tan Delta @ Uo (1e-3)

**Test Results – Global Perspective**

- Stability: STABLE, UNSTABLE
- Range of Instability in Monitored Withstand
- Splice Issues
- Terminating Damage

**Targeted Offline PD (VLF)**
Targeted Offline PD Test – Segment 6

Open symbols represent the anomalous TDR reflections.

PD Inception – local perspective

EVALUATION

Evaluation after Testing

Offline PD
- 15,000 ft actually tested
- Estimate
  - 15 discharge sites
    - 6 cable,
    - 9 accessories
  - 6 splices
  - <1 failure in 12 months from test
- Actual
  - 7 discharge sites
    - 0 cable,
    - 7 accessories
  - 25 splices
  - 0 failure in 7 months since test

Monitored Withstand
- 51,000 ft actually tested
- Estimate
  - 2 fails on test
  - 3 assessed for further consideration by loss
  - 0.5 failure in 12 months from test
- Actual
  - 0 fails on test
  - 6 assessed for further consideration by stability, tip up & loss
  - 1 failure (cable) in 8 months since test
After Testing...

- Actions have been performed by GPC.
  - Suspect splice investigated, actually broken neutral.
  - Damaged termination replaced.
  - Test excavations & Ground Penetrating Radar tests conducted, concluded that it was not practical to replace splices as planned

- System re-enforcements planned.
- All tested circuits have been left in service and are being monitored by GPC.
Performance of Diagnostics

- Performance evaluation primarily focuses on diagnostic accuracy.
- Diagnostic accuracies quantify the diagnostic's ability to correctly assess a circuit's condition.
- Accuracy must be assessed based on "pilot" type field test programs in which no actions are performed.
- Circuits must be tracked for a sufficient period of time.

Diagnostic Measurements and Failures

- Symptoms are difficult to relate to future failures unless they are in the extremes.

Objective of Diagnostic Tests

The target population contains both "Good" and "Bad" components:
- "Good" – Will not fail within diagnostic time horizon
- "Bad" – Will fail within diagnostic time horizon

"Bad" Components

Target Population

"Good" Components
Diagnostic Operation
Applying the diagnostic will separate the population into:
• No Action Required group
• Action Required group

But if the diagnostic is imperfect...

No Action Required  Action Required

Complimentary Diagnoses

Perspective
• Diagnostics make measurements in the field and find Anomalies.
• Detecting the presence of an Anomaly is, in our view, not sufficient.
• The goal, in our view, is to detect an Anomaly which leads to reduced reliability (failure in service) or compromised performance (severed neutrals – stray voltage).

In accuracy estimates we have used failures in service and interpreted the diagnostics as “Bad Means Failure.”
"Bad Means Failure" Accuracies

All Accuracies

Outline

- NEETRAC Overview
- CDFI Background/Overview
- Cable System Failure Process
- SAGE Concept
- Case Study: Roswell
- Diagnostic Accuracies
- Diagnostic Testing Technologies
- Accuracies Really Matter
- The Things We Know Now That We Did Not Know Before
- Selecting a Diagnostic Testing Technology
- Summary
Introduction

- A wide range of diagnostic techniques are commercially available.
- Tests are performed either offline (circuit de-energized) or online (energized) and by service providers or utility crews.
- Different voltage sources may be used to perform the same measurement.
  - DC
  - 60 Hz. AC
  - Very Low Frequency (VLF) AC
  - Damped AC (DAC)

Diagnostic Survey

- A survey of CDFI participants in 2006 was conducted to determine how diagnostics were employed.
- Survey was updated at the end of 2008.
- Survey results focused CDFI work on technologies currently used in the USA.
Survey of Use of Diagnostics

Technologies

- Simple Dielectric Withstand
- Dielectric Loss (Tan δ & Dielectric Spectroscopy)
- Time Domain Reflectometry (TDR)
- Online Partial Discharge (PD)
- Offline Partial Discharge (PD)
- Isothermal Relaxation Current (IRC)
- Recovery Voltage (RV)
- Combined Diagnostics
Diagnostic Context

- Extreme conditions are easy to decide what to do about.
- What to do about the ones in the middle?
- How to define the boundaries?

Simple Dielectric Withstand

Test Description
- Application of voltage above normal operating voltage for a prescribed duration.
- Attempts to drive weakest location(s) within cable segment to failure while segment is not in service.

Field Application
- Offline test that may use:
  - DC
  - 60 Hz. AC
  - VLF AC
  - Damped AC
- Testing may be performed by a service provider or utility crew.

Withstand Test Process

The goal is to have circuit out of service, test it such that “imminent” service failures are made to occur on the test and not in service.

Volages and Times for VLF covered in IEEE Std. 400.2
VLF Test Voltages

<table>
<thead>
<tr>
<th>VLF Test Voltages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable Rating (kV)</td>
</tr>
<tr>
<td>Test Voltage (kV)</td>
</tr>
<tr>
<td>0</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

- **Cosine-rectangular**
- **Sinusoidal**

---

Test Sequences

- **Simple VLF Withstand to IEEE400.2 Levels**
- **Time of failure in mins for failures > 15 mins**

- **Cumulative Length Tested in One Year (Miles)**
- **VLF Test Outcomes**

---

Data Generation from Diagnostic Measurement

- **Local Context**
- **Comparisons within one area**
**Separation with Simple VLF Outcomes**

- Area 1 is clearly different from the others.

**“Early” Phase Matters**

- 60% of failures on test occurred during “Early” phase.

**“Early” and “Hold” Phases**

- Difference between VLF and DC is primarily result of “Early” phase.

**“Early” Phase – Ramp Entry Example**

- In this case, 60% of the tests produced a failure before reaching the target test voltage.
**‘Early’ and ‘Hold’ Failure Mechanisms (VLF)**

- **‘Early’ Phase**
- **‘Hold’ Phase**

<table>
<thead>
<tr>
<th>Time on Test [Minutes]</th>
<th>Failures on Test [% of Total Tested]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.1</td>
</tr>
<tr>
<td>5.0</td>
<td>0.5</td>
</tr>
<tr>
<td>10.0</td>
<td>1.0</td>
</tr>
<tr>
<td>20.0</td>
<td>5.0</td>
</tr>
<tr>
<td>100.0</td>
<td>10.0</td>
</tr>
</tbody>
</table>

- **‘Early’ Phase – Hold Entry**

<table>
<thead>
<tr>
<th>Time on Test [Minutes]</th>
<th>Failures on Test [% of Total Tested]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>10.0</td>
<td>10.0</td>
</tr>
</tbody>
</table>

- **Simple Dielectric Withstand**

- **Global Context**
  - Comparison with many tests
  - Databases
  - Standards

- **Withstand Testing Experience**

  - IEEE Recommendation
  - IEEE 400.2 Range

- **9700 Conductor Miles**
- **>2000 Conductor Miles**
- **0.3 Conductor Miles**

CDFI Meeting - Aug. 19-20 San Ramon, CA
**Test Performance for Different Utilities**

<table>
<thead>
<tr>
<th>Utility</th>
<th>Time on Test (Minutes)</th>
<th>Failures on Test (% of 1000 ft Segments)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>10</td>
<td>10.00</td>
</tr>
<tr>
<td>A2</td>
<td>5</td>
<td>5.00</td>
</tr>
<tr>
<td>DI</td>
<td>3</td>
<td>3.00</td>
</tr>
<tr>
<td>SI</td>
<td>2</td>
<td>2.00</td>
</tr>
<tr>
<td>SI</td>
<td>1</td>
<td>1.00</td>
</tr>
<tr>
<td>SI</td>
<td>0.1</td>
<td>0.10</td>
</tr>
</tbody>
</table>

**Service Experience**

<table>
<thead>
<tr>
<th>Test Conditions</th>
<th>Time to Failure [Days]</th>
<th>Time to Failure [Days since test]</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 Min @ 2.5 U₀</td>
<td>472</td>
<td>1247</td>
</tr>
<tr>
<td>30 Min @ 1.8 U₀</td>
<td>637</td>
<td>2247</td>
</tr>
</tbody>
</table>

**Performance After Test – Pass/No Pass**

<table>
<thead>
<tr>
<th>Test Duration</th>
<th>Time to Failure for 1 % of Tested Segments [Days]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pass</td>
<td>133</td>
</tr>
<tr>
<td>No Pass - Repaired</td>
<td>215</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test Duration</th>
<th>Time to Failure for 1 % of Tested Segments [Days]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pass</td>
<td>36</td>
</tr>
<tr>
<td>No Pass - Repaired</td>
<td>1228</td>
</tr>
</tbody>
</table>

Segments that fail on test and subsequently repaired perform better in service.
What does this mean for Withstand?

- The technique is widely used by utilities
- Tested circuits display improved reliability
- Circuits normally Pass the tests
- Multiple / cascading failures are rare
- IEEE400.2 recommended times (30 mins) and voltages seem to give good service performance

What does this mean for Withstand?

- IEEE400.2 recommended times (30 mins) and voltages seem to give good service performance
- Modifications to IEEE400.2 recommendations need to be considered very carefully
- Voltage & test time cannot be determined independently
- Many test fails occur early in the test, useful information is revealed by tracking of these times / voltages of failure
- More failures on test does not mean fewer service fails

QUESTIONS

Day 2
Outline

• NEETRAC Overview
• CDFI Background/Overview
• Cable System Failure Process
• SAGE Concept
• Case Study: Roswell
• Diagnostic Accuracies
• Diagnostic Testing Technologies
• Accuracies Really Matter
• The Things We Know Now That We Did Not Know Before
• Selecting a Diagnostic Testing Technology
• Summary

Dielectric Loss (Tan δ)

Test Description

• Measures total cable system loss (cable, elbows, splices & terminations).
• May be performed at one or more frequencies (dielectric spectroscopy).
• May be performed at multiple voltage levels.
• Monitoring may be conducted for long durations.

Field Application

• Offline test that may use:
  – 60 Hz. AC
  – VLF AC
  – Damped AC
• Testing may be performed by a service provider or utility crew.
• Step voltage up to predetermined level with post test analysis

\[
\tan(\delta) = \frac{I_R}{I_c} = \frac{1}{\omega RC}
\]
Cable System Equivalent

Cable system (cable, splices, and terminations) is reduced to simple circuit.

Data Generation from Diagnostic Measurement

Local Context
Comparisons within one area
**Tan δ Data for EPR Cable Systems**

- Voltage (kV) vs. Tan δ (1e-3) graph showing Highest and Lowest Concern levels.

**Segments within a Feeder**

- Length Along Feeder (ft) vs. Tip Up in Tan Delta (1.5Uo - 0.5Uo) (1e-3) graph.

**Lengths within a Local Region**

- Length (ft) vs. Tan Delta (1e-3) graph.

**Global Context**

- Comparison with many tests, Databases, Standards.
Testing at Reduced Voltages

- **Tan-δ @ 2.0 Uo (1E-3)**
- **Tan-δ @ 1.5 Uo (1E-3)

Regression:
- CI: Confidence Interval
- PI: Prediction Interval

**Regression Results**:
- 100.0
- 10.0
- 1.0

**Tan Δ Interpretation**
- **Based on 258 Conductor Miles**
- **Tip Up**
- **Action Required**
- **Further Study**
- **No Action**

**Tan Δ Correlation with VLF Withstand**
- **Instructions**

**Tan Δ Performance Curves**
- **Performance Levels**
- **Error Bars**
- **Percent**

**Performance Levels**:
- **Action Required**
- **Further Study**
- **No Action**

**Performance Curves**:
- **Graph**

**Performance Graph**:
- **Y-axis**
- **X-axis**
- **Data Points**

**Legend**:
- **Filled**
- **Unfilled**
- **Basic Type**

**Performance Chart**:
- **Graphs**
- **Comparison**
- **Analysis**

**Analysis**:
- **Detailed**
- **Interpretation**

**Interpretation**:
- **Results**
- **Conclusion**

**Conclusion**:
- **Summary**
- **Recommendations**

**Recommendations**:
- **Action Required**
- **Further Study**
- **No Action**
What does this mean for Tan δ?

- Provides information on the whole cable system
- Most useful features are
  - Time Stability
  - Differential Tan δ (Tip Up)
- Higher loss correlates with increased probability of failure
- Comparisons provide very useful information
  - Length effects
  - Adjacent sections / phases
- Existing levels in IEEE Std. 400 are too conservative. Newer (higher) levels to be in IEEE Std. 400.2 revision

Time Domain Reflectometry

Test Description

- Measures changes in the cable impedance as a function of circuit length by observing the pattern of wave reflections.
- Used to identify locations of accessories, faults, etc.

Field Application

- Offline test that uses a low voltage, high frequency pulse generator.
- Testing may be performed by a service provider or utility crew.
Wet Joint

- Feeder had two splice failures just before the test.
- Water ingress was detected with the TDR.
- Failure on 01/17/2008 at detected water ingress location.
- Water ingress confirmed by tests and repair crew.

TDR Field Measurements

Lengths Tested

What does this mean for TDR?

- All diagnostics rely on the neutral, TDR helps to establish its condition.
- Length and accessory information are very important in establishing the context of diagnostic findings.
- Unusual TDR traces can diagnose unusual features in their own right.
Online Partial Discharge

**Test Description**
- Measurement and interpretation of discharge and signals on cable segments and/or accessories.
- Signals captured over minutes / hours.
- Monitoring may be conducted for long durations.

**Field Application**
- Online test that does not require external voltage supply.
- Testing typically performed by a service provider.
- Different implementations of the overall approach
- Assessment criteria are unique to each embodiment of the technology

Discharge Occurrence

- No PD
- PD
Local Context
Comparisons within one area

Distribution of PD along Lengths
- 5000 ft. portion of sample feeder
- Mixture of different PD levels for different sections and accessories.

Cable Section
Accessory
No PD
PD

Global Context
Comparison with many tests
Databases
Standards

Where is PD found?
- Accessory 54.0%
- Cable 46.0%
Level Based Reporting Systems

- Level-based (i.e. “1, 2, 3”, “Defer, Repair, Replace”, “Act, Don’t Act” etc.) reporting systems are increasingly common.
- Level systems, on their own, can have limited meaning for utilities.
- Levels clearly indicate a hierarchy
  - “5” worse than “4” “Replace” worse than “Defer”
- No sense of the magnitude of the difference
  - How much worse is “Act” than “Don’t Act” in terms of service performance?
- Comparisons/interpretation of different level-based reporting systems is difficult.

Need to associate meaning with the levels
**Alternate Interpretation**

<table>
<thead>
<tr>
<th>Original Level</th>
<th>Alternate Class (based on probability of failure)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&lt; 3</td>
</tr>
<tr>
<td>2</td>
<td>&lt; 3</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>18</td>
</tr>
<tr>
<td>5</td>
<td>89</td>
</tr>
</tbody>
</table>

Class **18** has 6 times poorer endurance than Class **3**  
Class **89** is 5 times poorer than Class **18**

**Probabilistic Approach – Online PD**

<table>
<thead>
<tr>
<th>TTF (days)</th>
<th>PD class 1</th>
<th>PD class 2</th>
<th>PD class 3</th>
<th>PD class 4</th>
<th>PD class 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>0.00</td>
<td>0.02</td>
<td>0.05</td>
<td>0.10</td>
<td>0.15</td>
</tr>
<tr>
<td>0.20</td>
<td>0.05</td>
<td>0.10</td>
<td>0.15</td>
<td>0.20</td>
<td>0.25</td>
</tr>
<tr>
<td>0.50</td>
<td>0.10</td>
<td>0.15</td>
<td>0.20</td>
<td>0.25</td>
<td>0.30</td>
</tr>
<tr>
<td>0.75</td>
<td>0.15</td>
<td>0.20</td>
<td>0.25</td>
<td>0.30</td>
<td>0.35</td>
</tr>
<tr>
<td>0.90</td>
<td>0.20</td>
<td>0.25</td>
<td>0.30</td>
<td>0.35</td>
<td>0.40</td>
</tr>
</tbody>
</table>

**Variability in Diagnostic Results**

<table>
<thead>
<tr>
<th>Level</th>
<th>Accessory</th>
<th>Cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>2</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>3</td>
<td>70%</td>
<td>70%</td>
</tr>
<tr>
<td>4</td>
<td>60%</td>
<td>60%</td>
</tr>
<tr>
<td>5</td>
<td>50%</td>
<td>50%</td>
</tr>
</tbody>
</table>

**How often is PD found?**

- Cable PD: 0.20 (levels 1-4)  
- Accessory PD: 0.15 (levels 1-4)  
- Total PD: 0.25 (levels 1-4)
Estimated Failure Reduction

<table>
<thead>
<tr>
<th>Time since Start [Days]</th>
<th>Accessory Cumulative Failures</th>
<th>Cable Cumulative Failures</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Levels 4/5 Replaced
All Segments Left in Service
14 Avoided Fails
45 Actions for 23 Avoided Fails

What does this mean for Online PD?

- Highly degraded systems most easily differentiated
- Not necessarily easy to deploy – sensor placement and manhole access can be challenging
- Signal analysis is labor intensive
- Data for level interpretation is available
- Trending is likely to be valuable, incorporating this in a level-based reporting system can be a challenge
- Baseline (when new) studies likely to be valuable
- Active failure mechanisms need to involve discharges
- Can localize to accessory and cable segments

Offline Partial Discharge

Test Description

- Measurement and interpretation of partial discharge signals above normal operating voltages.
- Signal reflections (combined with TDR information) allows location to be identified within cable segment.

Field Application

- Offline test that may use:
  - 60 Hz. AC service provider
  - VLF AC utility crew
  - Damped AC utility crew
- Step voltage up to pre determined level with post test analysis
Data Generation from Diagnostic Measurement

PD Pulse
- Amplitude: 140 mV, 180 pC
- Time: 0 to 1120 ns

PD Phase Resolved Pattern
- Amplitude [V]: 2.50E-1, 1.25E-1, 0, -1.25E-1, -2.50E-1
- Phase [Deg]: 0, 180, 360

PD Magnitude
- Measurement from Individual
- Max allowed for current production
- Max limit for 1970's production
- PD Measurement Voltage (Uo): 1.50 to 2.25

Max limit for current production
Local Context
Comparisons within one area

PD Charge Magnitude Distributions

Apparent Charge Magnitude [pC]

Percent

600 500 400 300 200 100 0

20 15 10 5 0

Apparent Charge Magnitude [pC]

Percent

2.4 2.1 1.8 1.5 1.2 0.9

18

16

14

12

10

8

6

4

2

0

PD Inception Voltage

Apparent Inception Voltage [UX]

Percent

2.4 2.1 1.8 1.5 1.2 0.9

2 4 6 8 10 12 14 16

XLPE

Global Context
Comparison with many tests
Databases
Standards
Location of PD

- 60.6% of PD sites detected in accessories
- 26.3% Terminations
- 39.4% Cable
- 34.3% Splices
- 60.6% of PD sites detected in accessories
- 222 Conductor Miles

Offline PD Test Sequence

- Testing sequence for 16,000 ft.
  - No PD
  - PD

PD Location

- Percent of Circuit Length
- Terminations
- Cable & Splices
- Approx. 1 PD Site/1000 ft
- Median = 0.96 PD Sites/1000 ft

PD Sites per Length

- Median = 0.96 PD Sites/1000 ft
- Approx. 1 PD Site/1000 ft
What does this mean for Offline PD?

- Highly degraded systems most easily differentiated
- Signal analysis can be labor intensive
- Data for level interpretation could be available
- Trending is likely to be very valuable
- Incorporating trending in a level-based reporting system can be a challenge
- Baseline (when new) studies likely to be very valuable
- Active failure mechanisms need to involve discharges
- Can localize to accessory and within short cable length within a segment

Isothermal Relaxation Current

**Test Description**
- Measures the time constant of trapped charges within the insulation material as they are discharged.
- Discharge current is observed for 15-30 minutes.

**Field Application**
- Offline test that uses DC to charge the cable segment up to 1kV.
- Testing is performed by a service provider.

Recovery Voltage

**Test Description**
- Similar to IRC only voltage is monitored instead of current

**Field Application**
- Offline test that requires initial charging by DC source up to 2kV.
- Testing is performed by a service provider.
What does this mean for IRC & RV?

- Use limited to evaluation studies in the laboratory
- Possibly too sensitive for field use

Combined Diagnostics

Multiple degradation mechanisms mean that two diagnostics are often better than one

Survey of Use of Diagnostics

- 41.7% No Testing
- 30.6% Testing - one technique
- 27.8% Testing - > one technique

Multiple Diagnostics
What Diagnostics are Combined

**Local**
- DC Leakage
- PD
- VLF Withstand

**Global**
- Tan δ
- TDR
- DC Withstand

Combined Diagnostics

Drawbacks of a Single Approach

- Each diagnostic looks for symptoms of one failure mechanism
  - Voids and water trees cannot generally be detected by a single technique
- Overlooks short term time evolution of diagnostic measurements
- Technique specific:
  - Withstand – No idea by how much segment passed
  - Tan δ – Cannot detect voids or electrical trees
  - PD – Cannot detect water trees (water filled voids)

Advantage of Multiple Diagnostics

Data Generation from Diagnostic Measurement
### Tan δ Ramp

<table>
<thead>
<tr>
<th>Time [min]</th>
<th>Tan-delta [1e-3] [p.u.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>1.2</td>
</tr>
<tr>
<td>3</td>
<td>1.4</td>
</tr>
<tr>
<td>4</td>
<td>1.6</td>
</tr>
<tr>
<td>5</td>
<td>1.7</td>
</tr>
</tbody>
</table>

### Tan δ Monitored Withstand

<table>
<thead>
<tr>
<th>Time [min]</th>
<th>Tan-delta [1e-3] [p.u.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>2.5</td>
<td>1.0</td>
</tr>
<tr>
<td>5</td>
<td>1.0</td>
</tr>
<tr>
<td>10</td>
<td>1.0</td>
</tr>
<tr>
<td>12.5</td>
<td>1.0</td>
</tr>
<tr>
<td>15</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Stability of Tan-delta monitored through the 15 minute withstand.

### Combined Diagnostics

#### After Repair...

<table>
<thead>
<tr>
<th>Time [min]</th>
<th>Tan-delta [1e-3] [p.u.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>1</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>0.0</td>
</tr>
<tr>
<td>3</td>
<td>0.0</td>
</tr>
<tr>
<td>4</td>
<td>0.0</td>
</tr>
<tr>
<td>5</td>
<td>0.0</td>
</tr>
<tr>
<td>6</td>
<td>0.0</td>
</tr>
<tr>
<td>7</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Elbow Failure Hampton Leas Segment HL_23_22

### After Failure

<table>
<thead>
<tr>
<th>Time [min]</th>
<th>Tan-delta [1e-3] [p.u.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>1</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>1.0</td>
</tr>
<tr>
<td>4</td>
<td>1.0</td>
</tr>
<tr>
<td>5</td>
<td>1.0</td>
</tr>
<tr>
<td>6</td>
<td>1.0</td>
</tr>
<tr>
<td>7</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Elbow Failure Hampton Leas Segment HL_23_22

After Failure
Global Context
Comparison with many tests
Databases
Standards

Tan δ Monitored Withstand

Cumulative Length Tested in One Year (Miles)

Withstand Test Outcomes

- UNSTABLE
- High Loss
- High TU
- Poor Stability

Monitored VLF Withstand to IEEE400.2 Levels

IEEE400.2 Levels

Time of failure in mins

Outline

- NEETRAC Overview
- CDFI Background/Overview
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- Diagnostic Accuracies
- Diagnostic Testing Technologies
- Accuracies Really Matter
- The Things We Know Now That We Did Not Know Before
- Selecting a Diagnostic Testing Technology
- Summary

QUESTIONS
Accuracies Revisited

Why do they matter?

Recall the Example...

No Action Required

Avoided Corrective Actions

Action Required

Avoided service failures

Incorrect Diagnosis

No Action Required

Future service failures

Action Required

Unneeded Corrective Actions
Considerations

- Diagnostic program economic calculations are based on ability to predict future failures.
- Total diagnostic program cost is more sensitive to certain elements than others.
  - Failure Rate
  - Diagnostic Accuracy
  - Failure Consequence
Diagnostic Accuracy Complications

- Time is a critical factor in the assessment of accuracy.
  - Failures do not happen immediately after testing.

- Two approaches to computing diagnostic accuracy.
  - “Bad Means Failure” Approach
  - “Probabilistic” Approach

Failures Over Time

Year 5

No Action Required

Action Required

Accuracy Over Time – “Bad Means Failure”

<table>
<thead>
<tr>
<th>Time [Years]</th>
<th>No Action Required Accuracy</th>
<th>Action Required Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100</td>
<td>?</td>
</tr>
<tr>
<td>2</td>
<td>?</td>
<td>Action Required Accuracy</td>
</tr>
<tr>
<td>4</td>
<td>System Changes</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Additional Aging</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Increased Load</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Probabilistic Approach - Tan δ

- POT (Passed On Time)
- Elapsed Time between test and failure in service at May 09 (Month)

- Action Required
- Further Study
- No Action
QUESTIONS

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The Things We Know Now That We Did Not Know Before

By Diagnostic Technique
CDFI Work in Lab and Field

- Dielectric Withstand
  - Simple
  - VLF Laboratory Study
- Dielectric Loss
- VLF Tan δ
  - Monitored Withstand
- Partial Discharge
- Offline 60 Hz.

Dielectric Withstand

- Withstand techniques are most widely used diagnostic in the USA.
- Most utilities use VLF (either sine or cosine-rectangular) in their withstand programs.
- Test duration and voltage are critical to performance on test and in service.
- Explored the concept of “Monitored” Withstand tests.

Length Distribution (Overall)

Wide variability in circuit lengths
Length Adjustments

• Comparison of withstand failure on test rates must include length adjustments.

Choose an appropriate base length

• Base length must be a meaningful length (50 ft is probably not a useful length).

• Two sets of censored segments:
  – Pass Segments - All segments censored at test duration
  – No Pass Segments
    • 1 failed segment
    • remaining segments censored at failure time

• Multiple failure modes must be dealt with appropriately.

Performance at longer test times can be predicted.

Length Weighted Average FOT

<table>
<thead>
<tr>
<th>Time on Test [Minutes]</th>
<th>Length Weighted Average FOT [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 Mins</td>
<td>2.7%</td>
</tr>
<tr>
<td>60 Mins</td>
<td>5.0%</td>
</tr>
<tr>
<td>120 Mins</td>
<td>17.5%</td>
</tr>
</tbody>
</table>

Utility I – Hybrid System
Overview

• Test program combining aging at $U_0$ with multiple applications of high voltage VLF.
• Uses field aged cable samples - one area within one utility.
• Evaluate the effects of
  – Voltage and time on the performance on test and
  – Subsequent reliability during service voltages.

Primary Metric
Survival during aging and testing

Secondary Metrics
– Before and after each VLF application, PD at $U_0$
– Between Phase A & B IRC, PD (AC 2.2$U_0$, DAC), Tan $\delta$
Voltage Effect on Times to Failure

Both curves show that higher voltage leads to increased failure rate.

Phase I & II - Uo / RT ageing, Sine

Test Voltage [Uo]  | Time to 10% Failure [mins]
------------------|---------------------------
2.2               | 180
2.4               | 160
2.6               | 140
2.8               | 120
3.0               | 100

Phase III - 2Uo / 45°C ageing, Cosine

Both curves show that higher voltage leads to increased failure rate.

Test Voltage [Uo]  | Time to 10% Failure [mins]
------------------|---------------------------
2.2               | 180
2.4               | 160
2.6               | 140
2.8               | 120
3.0               | 100

Failure Analyses - Trees & Defects in Cables

Dielectric Withstand

Distance A long Cable (ft)  | Failed Samples
----------------------------|----------------
25                           | D
20                           | C
15                           | B
10                           | A
5                            | DEFECT
0                            | LARGE WATER TREE
5                            | MEDIUM WATER TREE
10                           | SMALL WATER TREE

VLF Test Program Summary

- Analysis of Phase A is complete.
- Phase B (2U₀ aging, 45°C Cosine Rectangular) underway.
- Phases A & B show that no VLF exposed samples have failed under 60 Hz aging @ U₀ & 2U₀.
- Phase B tests shows two samples without VLF exposure failed during 60 Hz aging @ 2U₀.
- VLF failures on test:
  - Less than 15 mins: 12% (2 failures)
  - 15 – 60 mins: 71% (12 failures)
**Prevailing View – Tan Delta**

- Importance
- **Tan δ**
- Tip Up
  - [2\(U_0\) – 1\(U_0\)]

**CDFI Suggestion – Tan Delta**

- Importance
- **Tan δ**
- Time Stability
- Tip Up
  - [1.5\(U_0\) – 0.5\(U_0\)]
- **Tan δ**
  - [\(U_0\)]

**Tan δ Time Stability**

- Breakdown Performance Rank
- Breakdown Frequency
  - [0.1 Hz (1.5 \(U_0\))]

**VLF Tan Delta of Cable Systems**

- Can segregated based on areas where the curves break
- Define areas that are "normal" and "unusual"
- >650 segments
- Mean Length 2000ft
- Total length >250 conductor miles
CDFI Meeting - Aug. 19-20 San Ramon, CA

Cable System – Global Assessment

- Tan δ

Unfilled Polyolefin Insulations
- Action Required
- Further Study
- No Action

Tip Up (1e-3)

Service Performance / Accuracy

- Elapsed Time between test and failure in service at May 09 (Month)

- Tan δ

- Percent

CDFI Work

- Analysis of historical PD field test data
- Classification
- Characterization of field samples by PD measurement in laboratory.
- Feature Extraction for Classification
PD Charge Magnitude Distributions

PD Inception Voltage

Multi Feature Classification

Classification - PD Magnitude & PDIV

pC and PDIV are not sufficient to get high classification accuracy.
<table>
<thead>
<tr>
<th>Cluster No.</th>
<th>Feature Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pos. Phase Range [deg]</td>
</tr>
<tr>
<td>2</td>
<td>Pos. Mean Phase [deg]</td>
</tr>
<tr>
<td>3</td>
<td>Pos. Qmax [pC]</td>
</tr>
<tr>
<td></td>
<td>Neg. Qmax [pC]</td>
</tr>
<tr>
<td></td>
<td>Neg. Qmean [pC]</td>
</tr>
<tr>
<td></td>
<td>Pos. Qmean [pC]</td>
</tr>
<tr>
<td></td>
<td>Pos. Mean Energy [pC*V]</td>
</tr>
<tr>
<td></td>
<td>Pos. Max Energy [pC*V]</td>
</tr>
<tr>
<td></td>
<td>Neg. Max Energy [pC*V]</td>
</tr>
<tr>
<td>4</td>
<td>Neg. Phase Range [deg]</td>
</tr>
<tr>
<td>5</td>
<td>Neg. Mean Phase [deg]</td>
</tr>
<tr>
<td>6</td>
<td>Mean Energy Ratio</td>
</tr>
<tr>
<td>7</td>
<td>Nw [pulses/cycle]</td>
</tr>
</tbody>
</table>

**Partial Discharge Diagnostic Features**

- 50% Similarity Level
- 15.18, 43.45, 71.73, 100.00

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**QUESTIONS**
Selecting a Diagnostic Technology

Knowledge-Based System

KBS

- Selecting the right diagnostic is not easy.
- No one diagnostic covers everything.
- How you measure is influenced by what you do with the results.
- The KBS captures the experience and knowledge of people who have been operating in the field

Knowledge Based Systems

- Knowledge-Based Systems are computer systems that are programmed to imitate human problem-solving.
- Uses a combination of artificial intelligence and reference to a database of knowledge on a particular subject.
- KBS are generally classified into:
  - Expert Systems
  - Case Based Reasoning
  - Fuzzy Logic Based Systems
  - Neural Networks

Extruded Cable Diagnostics
KBS Example

Short Listing of Diagnostic Approaches

Impact of Remedial Action

- Hybrid Cable System
- Most service failures occur in Accessories
- Usual remediation is by replacement of cable sections

<table>
<thead>
<tr>
<th>System Component</th>
<th>Portion [%]</th>
<th>Service Failure Rate</th>
<th>Age [yrs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE</td>
<td>33</td>
<td>Medium</td>
<td>20 - 30</td>
</tr>
<tr>
<td>EPR</td>
<td>42</td>
<td>Low</td>
<td>0 - 10</td>
</tr>
<tr>
<td>Paper</td>
<td>25</td>
<td>High</td>
<td>40 - 50</td>
</tr>
</tbody>
</table>

Hybrid Cable System
What we have learned about diagnostics (1)

1. A developing database of field failure diagnostic data shows that different diagnostic techniques can provide some indication about cable system condition.

2. Even if the diagnostics themselves are imprecise, diagnostic programs can be beneficial.

3. Benefits can be quantified, however this is not simple and requires effort.

4. Many different data analysis techniques, including some nonconventional approaches, are needed to assess diagnostic effectiveness.

5. Utilities HAVE to act on ALL replacement/repair recommendations to get improved reliability.

Summary
What we have learned about diagnostics (2)

6. PD, VLF, DC and Tan δ & VLF withstand tests detect problems in the field and can be used to improve system reliability.

7. It is difficult to predict whether or not the problems/defects detected by PD or Tan δ will lead to failure.

8. PD assessments are good at establishing groups of cable system segments that are not likely to fail.

9. Tan δ measurements provide a number of interesting features for assessing the condition of cable systems.

10. Tan δ & PD measurements require interpretation to establish how to act.

What we have learned about diagnostics (3)

11. Interpretation of PD measurements is more complex than interpretation of Tan δ measurements.

12. IRC & RV are particularly difficult to deploy in the field.

---

**Diagnostic Information**

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Information Content</td>
<td></td>
</tr>
<tr>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>VLF</td>
<td>DAC</td>
</tr>
<tr>
<td>Simple</td>
<td>Some Skill</td>
</tr>
</tbody>
</table>

**Ease of Utility Implementation**

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Time</th>
</tr>
</thead>
<tbody>
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<td>Simple</td>
<td>Some Skill</td>
</tr>
</tbody>
</table>

**Combined Diagnostics**
Diagnostic Information

Adaptive Test Protocols
Tests adjusted in real time according to analysis/decisions made during each test.

Preset Test Protocols
Analysis of data performed after tests are completed.

Ease of Utility Implementation
Combined Diagnostics
Reflections

- Approach to data analysis established in CDFI
- Many questions answered, there still remain gaps in our understanding of:
  - Benefits
  - Distinguishing anomalies from weaknesses
- Answers will come with continued analysis of field test data (diagnostic tests followed by circuit performance monitoring) as well as controlled laboratory tests.
- The potential value of continued analysis is high.

CDFI Phase 1 Extension

Schedule: October 1, 2009 - September 30, 2010

Tasks
- VLF Withstand
- Defects
- Field Surveys
- Regional Meetings

CDFI Phase II

Schedule: January 2010? (3 Year Duration)

Tasks
- High Voltage Testing
- Commissioning Tests
- Field Demonstrator
- Field Testing
  - Revisits/Trending
  - Challenging Utility Regions
- Diagnostic Reference Handbook
- Knowledge-Based System

Phase II Participants
- Current CDFI
- EPRI
- DOE
- New entrants

QUESTIONS